Variability of groundwater recharge in the Sahel: piezometric survey of the Continental Terminal aquifer (Niger)

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Abstract The hydrological and hydrogeological survey of the HAPEX-SAHEL area (8000 km$^2$ near Niamey, Niger) has pointed out the heterogeneity of surface and subsurface flows, even in a simple sedimentary context. The three year observations of 60 pools and 250 wells reveal the major contribution of small endoreic pools to the recharge processes of the Continental Terminal phreatic aquifer. Piezometric fluctuations throughout the year are almost always lower than 1 m, but can reach up to 9 m. Infiltration rates are calculated from volumes assessment of pools and from fluctuations of groundwater level; the average groundwater recharge is 10% of the annual rainfall, i.e. 50 mm per year. Even with the recent light rising of the piezometric level, some of the zones that are much more sensitive to the recharge variations have very poor resources.

INTRODUCTION

Frequent and severe droughts during the 1970s and 1980s have emphasized the extreme fragility of the environment in the Sahel. The rapidly expanding population (3% per year) requires more water in a country where groundwater constitutes the most reliable and often the only permanent water resource. Even in sedimentary basins, more privileged than basement areas, survey of aquifers in quantity and quality is essential for their efficient management.

In particular, when restricting the exploitation to the renewable part of the resource, description and quantification of the recharge processes are essential. Often, estimates of infiltration in the Sahel are based on scarce data or questionable methods. On the contrary, as part of HAPEX SAHEL (Hydrologic Atmospheric Pilot Experiment in the Sahel), this hydrogeological study consists of a three year survey of 60 pools and 250 wells distributed over 8000 km$^2$ near Niamey (Niger).

The studied area is bounded by the parallels 13°N and 14°N, the meridians 2°E and 3°E, north of the Niger River. The outcropping sediments are tabular deposits of late Tertiary "Continental Terminal" (sand, silt, clay and lateritic intercalations) laying over the metamorphic and granitic basement in the west and early Tertiary "Continental Intercalaire" in the east. Depending on its thickness, with variation up to 200 m, Continental Terminal contains one to three water-bearing levels. The depth to the phreatic water table is between 2 and 75 m (median 35 m).
The area is a patchwork of lateritic plateaux (24% of the total area) and sandy valleys. During the rainy season, the surface runoff concentrates in numerous small endoreic basins; their temporary pools contribute in a major way to the recharge processes.

VARIABILITY OF RAINFALL

The rainfall variability in time and space over the Sahel is well known. On a large scale, the average rainfall regularly decreases from south to north by about 1 mm km$^{-1}$. The interannual variability is illustrated by the records in Niamey between 1905 and 1992: the extremes of annual rainfall are 281 mm in 1915 and 939 mm in 1909. For the last 30 years, the average is 541 mm with a low of 319 mm in 1984 and a high of 813 mm in 1967.

With a high density of raingauges (one per 200 km$^2$) in the HAPEX SAHEL degree square (HSds), Taupin et al. (1993) show an annual rainfall difference of 100% over a distance of 27 km in 1991. The average rainfall of the HSds is 419 mm in 1990, 522 mm in 1991 and 513 mm in 1992.

In fact, the annual rainfall has little relation to the annual infiltration, for groundwater recharge depends on the distribution in time of the rains and their intensities.

VARIABILITY OF PIEZOMETRIC FLUCTUATIONS

The piezometric survey of the HSds phreatic aquifer consists of monitoring about 250 wells with a period between two measurements varying from one week to four months. This survey yielded 300 measurements in 1991, 1000 in 1992 and even more in 1993. Seven automatic level recorders provide data every 15 minutes. Nearly all of the monitored wells are close to the villages, i.e. outside the lateritic plateaux. Therefore, the piezometric network over represents the sandy slopes and valley bottoms.

The piezometric framework (Fig. 1) is unchanged throughout the year. There is no main direction for the groundwater flow. The eastern part of the aquifer has lower hydraulic gradients and an almost certainly closed piezometric depression.

The piezometric response to infiltration depends on the recharge flow, the hydrodynamical characteristics of the aquifer and the distance from the recharge point, in the case of localized infiltration. Most of the wells over the HSds have a small annual fluctuation: in 1992, the median is 0.6 m. Only 5 wells have an amplitude between 5 and 9 m; 17 others are between 2 and 5 m (Leduc & Lenoir, 1994).

The majority of wells with high fluctuation belong to two zones. The first one is the northwest of HSds, with significant heterogeneity, which is also appearing in hydrochemical data. This heterogeneity is related to the wedging out of Continental Terminal over the basement. The aquifer is thin and the resources weak. The second one is a region, about 30 km east of Niamey, which has the highest piezometry in the HSds and also the most varying wells.

In fact, most of these highly varying wells are close to a pool. Infiltration into the valley bottoms creates piezometric mounds whose dimensions can exceed a few hundred of metres in radius and 10 m in maximum height.
Variability of groundwater recharge in the Sahel

There is no relation between depth to the water table and annual fluctuation. In the Dallol Bosso, a fossil valley bordering the HSds in the east, the water table is a few metres below the surface and the annual amplitude is the same as elsewhere in the aquifer.

Depending on the large variability in time of the piezometric response, wells can be classified into three categories:
- wells without any significant reaction throughout the year; infiltration is weak or slow;
- wells with a rather regular rise of the water level; recharge processes match with a classical description of flow through porous media; some wells reach their maximum during the rainy season, others several weeks after its end;
- wells, in most cases next to a pool, with rapid response to major flood events, due to a high ratio transmissivity/storativity or preferential paths (e.g. roots and termite hills); the groundwater level can rise just a few hours after a flood.

In the third case, the reaction of a well close to a pool can evolve: the aquifer response, low at the beginning of the rainy season, becomes more pronounced one month later. This is explained by the increase of the water content in the unsaturated zone (Fig. 2).

Over the whole HSds, 34 wells were already measured in 1965. It would seem there is no significant change of the water level compared to the 1992/1993 measurements (median and average close to 0 m).

About 30 wells of the HSds central zone have been monitored monthly during a 7 year period; this constitutes a rare piezometric record in Niger. The 1992/1993 observations confirm it as a homogeneous region with a low annual amplitude. The regular rise of the water level since 1987, from 5 to 25 cm per year, evidences the reconstitution of the groundwater resources after the 1970s and 1980s droughts (Fig. 3).
VARIABILITY OF POOLS

According to geomorphological and hydrological criteria, endoreic systems are classified into three groups:
- pools on plateau with ferruginous cuirass: small drainage basins (1 to 3 $10^5$ m$^2$), impervious substratum, hardened surface thick and rather continuous;
- pools in valley bottoms closed by accumulation of eolian sands: drainage basins from 1 to 10 km$^2$, substratum of alluvial or eolian sands sometimes clogged by recent lacustrine sediments;
- pools on former water courses, inactive yet: substratum of alluvial sands, which can also be clogged.
In the HSds, relative areas for these three systems are estimated at about 20, 40 and 20% respectively. The unclassified rest is composed of very flat dunes without any obvious pool or hydrological structure.

The decrease in the water level of the pools is highly variable: it can be slow (plateau pools especially), rapid or very rapid (most of the valley bottom pools). Each pool has its own hydrological process and therefore a specific distribution of water between the atmosphere and the aquifer.

In spite of this diversity, some common characteristics appear:
- except for very few pools partially supplied with water from artesian boreholes, the pools depend on surface runoff during the rainy season;
- daily losses of water are often much higher than evaporation;
- the pool lowering, obvious after every flood, depends on flood volume, morphology and pedology of the bed and banks (Desconnets et al., 1993).

Three pools, characteristic of the three systems, are detailed below. The Wankama pool is in the bed of a fossil river; the Samadey pool is in a closed valley 10 km southeast of Wankama and Bazanga is on a lateritic plateau 15 km southwest of Wankama. Figure 4 shows the relationship between the daily loss of water (i.e. infiltration and evaporation) and the water level of the pool. In the closed valley pool, infiltration is present even for very low water heights. On the other hand, infiltration starts in fossil valley or plateau pools only above a certain level, corresponding to the limit of the clogged zone. The accumulation of clay in the central lower part of the pool restricts vertical infiltration. In fact, groundwater recharge from the pool is mainly due to lateral percolation through the more permeable banks.

The evaluation of aquifer recharge for each type must consider the daily loss of water (0 to 3000 m³ per day in Bazanga, 0 to 300 000 in Samadey), the duration of infiltration (several hours or days in Samadey, more than 6 months in Wankama) and the role of evaporation (extremely weak in Samadey, significant in Bazanga).

**EVALUATION OF RECHARGE**

Recharge can be estimated from the water budget of the pools and also from its piezometric impact.

For our three examples, the 1992 water budget is detailed in Table 1. Samadey pool has accumulated at the end of the rainy season a very large volume (nearly 500 000 m³), which is totally infiltrated. On the contrary, Bazanga has a small final stocked volume. For plateau pools, uncertainty is higher because the drainage basin is generally small, relative to the total plateau area. Furthermore, the plant transpiration can significantly increase the real evaporation (cattle watering can be neglected). Contribution of plateau pools to the aquifer recharge is therefore much weaker than calculated in the table.

The contribution of the lateritic plateaux to the aquifer recharge cannot be directly evaluated from piezometric observations. It is certainly very limited as suggested by S. Galle (personal communication) who has shown that bare soil areas are quite impervious and, outside the small plateaux pools, infiltration could take place only in vegetation strips.

For a central site of $20 \times 30$ km$^2$, the median piezometric amplitude is 40 cm. With an annual fluctuation estimated at about 10 cm beneath the plateaux, which represents a quarter of the total area, and an average porosity of 15%, this means an annual...
Table 1 Water budget in Samadey, Bazanga and Wankama in 1992.

<table>
<thead>
<tr>
<th></th>
<th>Basin area (km²)</th>
<th>Total rain (mm)</th>
<th>Runoff/rain (%)</th>
<th>Pool stock (m³)</th>
<th>Infil. pool stock (%)</th>
<th>Infil./rain (%)</th>
<th>Type of pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samadey</td>
<td>6.3</td>
<td>343.5</td>
<td>22.5</td>
<td>488 213</td>
<td>98.9</td>
<td>22.3</td>
<td>closed val.</td>
</tr>
<tr>
<td>Bazanga</td>
<td>0.3</td>
<td>500.5</td>
<td>23.0</td>
<td>34 468</td>
<td>72.7</td>
<td>16.7</td>
<td>plateau</td>
</tr>
<tr>
<td>Wankama</td>
<td>1.5</td>
<td>394.5</td>
<td>24.4</td>
<td>144 432</td>
<td>93.6</td>
<td>22.8</td>
<td>val. bottom</td>
</tr>
</tbody>
</table>

Fig. 4 Water level (abscissa in m) and daily water loss (ordinate in 10³ m³) for 3 typical pools.
recharge of about 50 mm, i.e. about 10% of annual rainfall. This central site is the most homogeneous part of the HSds. For the entire HSds, the median amplitude is larger (60 cm).

CONCLUSION

The role of pools in the recharge of the phreatic aquifer is obvious: the high, rapid rise of the level close to the pools and its attenuation as distance from pool increases prove the importance of infiltration in valley bottoms.

In spite of many potential uncertainties, volume lost by infiltration in the pools is in agreement with volume reaching the aquifer. Even if not the only one, this is the primary process of groundwater recharge.

The renewal rate of the phreatic aquifer is estimated at about 1 to 2% per year. The major part of Continental Terminal in the HSds is thick enough to carry through a period of poor infiltration. Nevertheless, the northwestern zone is exposed yearly to a partial drying out at the end of the dry season, mainly because of its position at the border of the aquifer and its limited wet thickness. The other potential resource, the granitic basement, is insufficient. This situation persists northwards outside the HSds along the western border of the aquifer.

REFERENCES

